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THE EFFECTS OF USING NOISE REDUCTION TURBOFAN ENGINE NOZZLE DESIGNS ON A TURBOJET ENGINE

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The Effects of Using Noise Reduction Turbofan Engine Nozzle Designs on a Turbojet Engine

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Abstract: Aircraft noise is a complex topic which is projected to increase with the increasing number of aircraft and size of the engines. Turbine-powered aircraft produce sounds that are considered pollutants at certain decibel levels. Turbofan engines are inherently quieter than turbojet engines for a given level of thrust. The purpose of this research is to determine if current turbofan noise reduction nozzles could reduce the amount of noise for turbojet engines at two different thrust levels. Three turbofan engine nozzles were designed and tested on a turbojet engine. Decibel levels of 30 frequencies for each of the nozzles were compared to the original turbojet nozzle using an indoor turbine power plant thrust cell. Six samples of thirty decibel levels and frequencies were recorded at idle and at a higher thrust level. Additional parameters of engine operation were also compared (oil pressure, oil temperature, exhaust gas temperature, thrust lever position, and fuel consumption). Results were evaluated in two ways: (1) the effect of each nozzle design in reducing noise by decibel level or frequency shift as compared to the original nozzle, and (2) change in the efficiency of the engine operation of each nozzle design as compared to the original nozzle. The turbofan nozzle designs did not result in any major improvements in reducing the overall noise levels. However, there were reductions of dB levels for some frequencies. Frequency shifts were apparent in all nozzle designs and most shifts were toward the higher frequencies.

Keywords: *Exhaust nozzle, Noise reduction, Turbojet*

1: Introduction

The current world air transportation fleet is approximately 23,000 and will double to 44,500 aircraft by 2033 (Forsberg, 2014). A flight tracking organization reported as many as 13,256 aircraft are flying in the world at any one time (Flightradar24, 2016). Potential issues related to this projected increase include congestion at airports and airspace, air pollutants in the form of chemical by-products of the combustion in the turbine and reciprocating engine designs. Modern turbine engine fuel is primarily kerosene, the same fuel used to heat homes in portions of the U.S. Kerosene, a flammable hydrocarbon oil, is a fossil fuel. Burning fossil fuels primarily produces carbon dioxide (CO_2) and water vapor (H_2O). Other major emissions are nitric oxide (NO) and nitrogen oxide (NO_2), which together are called NO_x, sulfur oxides (SO_2), and soot (NASA, 2008).

Another important type of potential pollutant is the amount of noise created by aircraft engines. In addition to the increase in fleet size, the engines themselves have increased in size, thus increasing the amount of noise pollution. Aircraft and airport noise are complex subject matters which have been studied for decades and are still the focus of many research efforts today. The Federal Aviation Administration (FAA) regulates aircraft through international standards (FAA, 2016). These standards are applied when an aircraft is acquiring its airworthiness certification, and requires that aircraft meet or fall below designated noise levels. For civil jet aircraft, there are four stages of noise, with Stage 1 being the loudest and Stage 4 being the quietest. As of December 31, 2015, all civil jet aircraft, regardless of weight, were required to meet Stage 3 or Stage 4 to fly within the contiguous U.S. The FAA has begun to phase out the older, noisier civil aircraft, resulting in some stages of aircraft no longer being in the fleet (FAA, 2016).

Aero gas turbine engines have an exhaust system that passes the turbine discharge gases to the atmosphere at a required velocity and at a required direction. The velocity and pressure of the exhaust gases create the thrust in the turbojet engine. The design of the exhaust system therefore, exerts a considerable influence on the performance of the engine (Rolls-Royce, 1996). The exhaust gases pass to the atmosphere through the exhaust, which is a convergent duct, thus increasing the gas velocity. In a turbojet engine the exit velocity of the exhaust gases reach the speed of sound during most operating conditions (Rolls-Royce, 1996). The sound produced is caused by the shear turbulence between the relatively calm air outside the engine and the high-velocity jet of hot gases emanating from the nozzle. The noise caused by the jet exhaust is termed broadband noise. The broadband noise consists of all frequencies audible to the human ear (Kroes & Wild, 1995).

Turbofan engines are inherently quieter than turbojets for a given level of thrust. A turbofan thrust is developed by turning a fan with a turbine engine that accelerates a larger amount of air to a lower velocity than do turbojets.

Turbojet thrust is developed solely by the turbine engine. Therefore, for a given thrust, the fanjet's discharge contains less energy (but more mass) as it exits the engine, and so produces less noise. Turbofan engines are commonly used on commercial transports due to their advantage for higher performance and lower noise (NASA, 2007).

The intensity of the sound at any given distance is largely a function of the frequency of the pressure disturbances in the exhaust. Lower frequencies travel further without losing energy, and so are heard at a greater distance. An analogy commonly cited is that of a marching band where the bass drums are heard well in advance of the higher frequency instruments (trumpets, flutes, clarinets, etc.). The noise emitted by turbojet engines is of a much lower frequency than that produced by a turbofan engine, which is another reason that turbojets are said to be "noisier" than turbofan engines. Early turbine-powered aircraft using turbojet engines were retrofitted with nozzle modification devices referred to as "Hushkits" to comply with the first stages of federal regulation. The effect of this nozzle is to reduce the size of the individual jet stream and increase the frequency of the sound (Kroes & Wild, 1995). These nozzle modifications had some negative aspects; they reduced the aerodynamics of the aircraft and engine efficiency by increasing fuel consumption (Mola, 2005). The level of sound produced by the turbojet and turbofan engines and the types of exhaust nozzle designs is the focus of this research. The purpose is to see if using noise reduction nozzle designs currently used on turbofan engines reduce noise on a turbojet engine

2: Materials and Methods

Three aspects of turbojet noise were considered in designing the overall research project. First, sound level, that is usually defined in terms of Sound Pressure Level (SPL). SPL is actually a ratio of the absolute sound pressure and a reference level, (usually the Threshold of Hearing or the lowest intensity sound that can be heard by most people). SPL is measured in decibels (dB), because of the incredibly broad range of intensities that humans can hear (HLAA, 2003). Second, the noise emitted by a turbojet engine consists of more low frequencies than that produced by a turbofan engine (Wyle Acoustics Group, 2001). Third, it is highly desirable to reduce the jet noise without changing the engine cycle. Over the years, this has proven to be a challenging problem (NASA, 2007). To address these three aspects, equipment to measure dB levels, determine frequencies ranges, and monitor the effects on engine cycle were selected.

Three nozzle designs that were developed in the past fifteen years for turbofan engines were installed and tested on a Pratt Whitney JT-12-8 turbojet engine. The test nozzle designs included a Chevron (U.S. Patent No. 6,360,528 B1, 2002) and two sizes of Tab designs (U.S. Patent No. 6,487,848 B2, 2002) (see Figure 1). The basis for design and fabrication of the nozzle were derived from previous research, patent sketches, and photographs. All the nozzles were designed and fabricated by the PI.

A Large Tab nozzle was designed with 10 two-inch tabs surrounding the forty-inch circumference of the exhaust opening. The tip of each tab was set in toward the exhaust path by thirty degrees. A Small Tab nozzle was designed with 20 one-inch tabs surrounding the forty-inch circumference of the exhaust. The tips of each of these tabs were set in toward the exhaust path by forty-five degrees. These were fabricated from HR ASTM A1011 CS steel. The third nozzle was a Chevron design that was fabricated from the original manufacturer’s nozzle. It was modified and has 20 two-inch Chevrons surrounding the forty-inch circumference set in toward the exhaust path by thirty degrees.

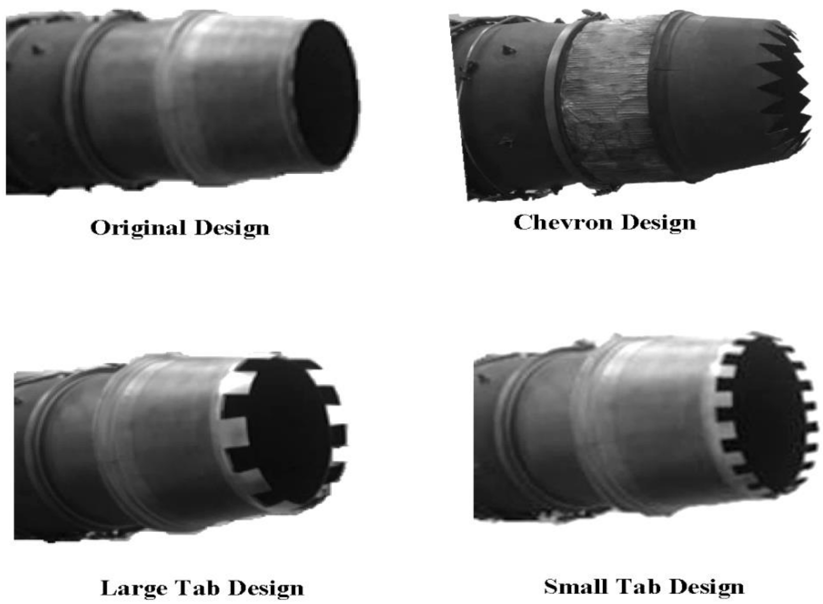


Figure 1: Nozzle Designs

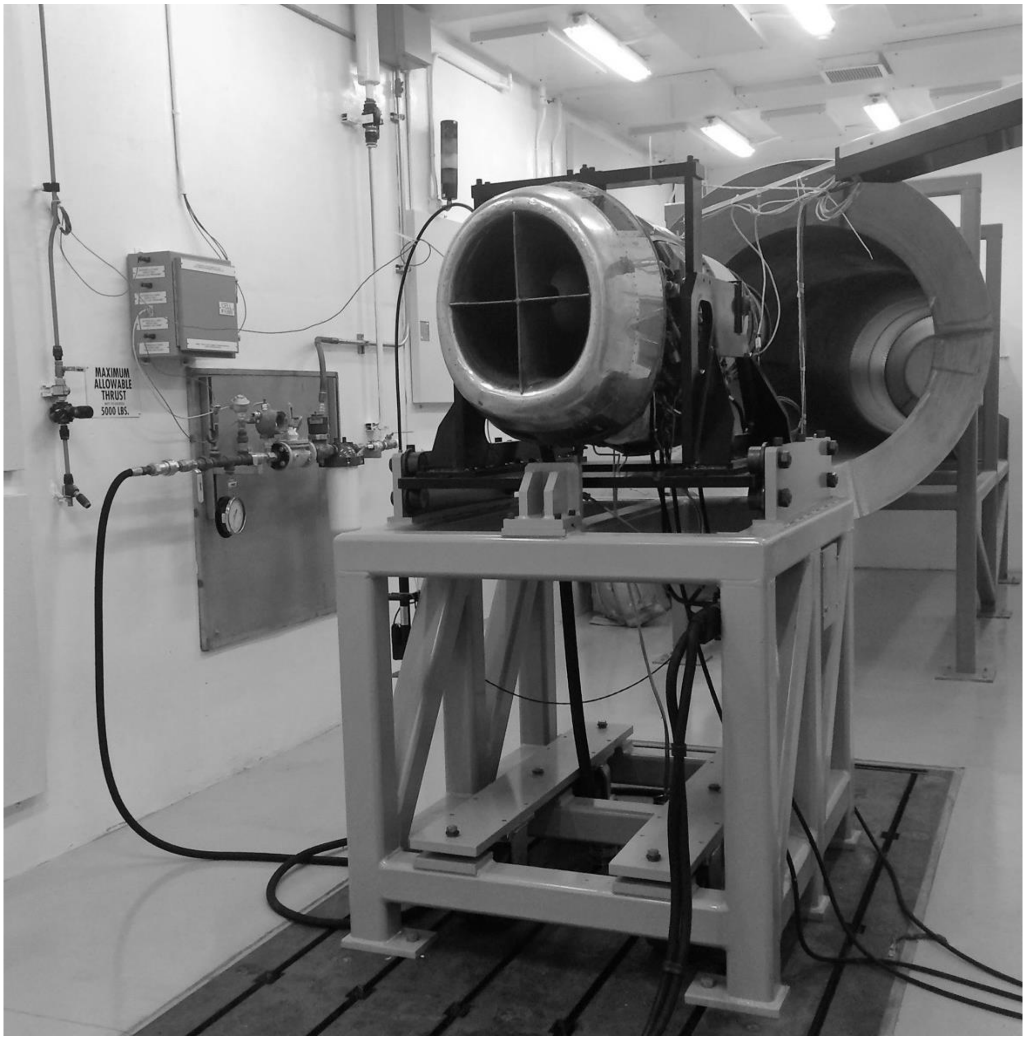


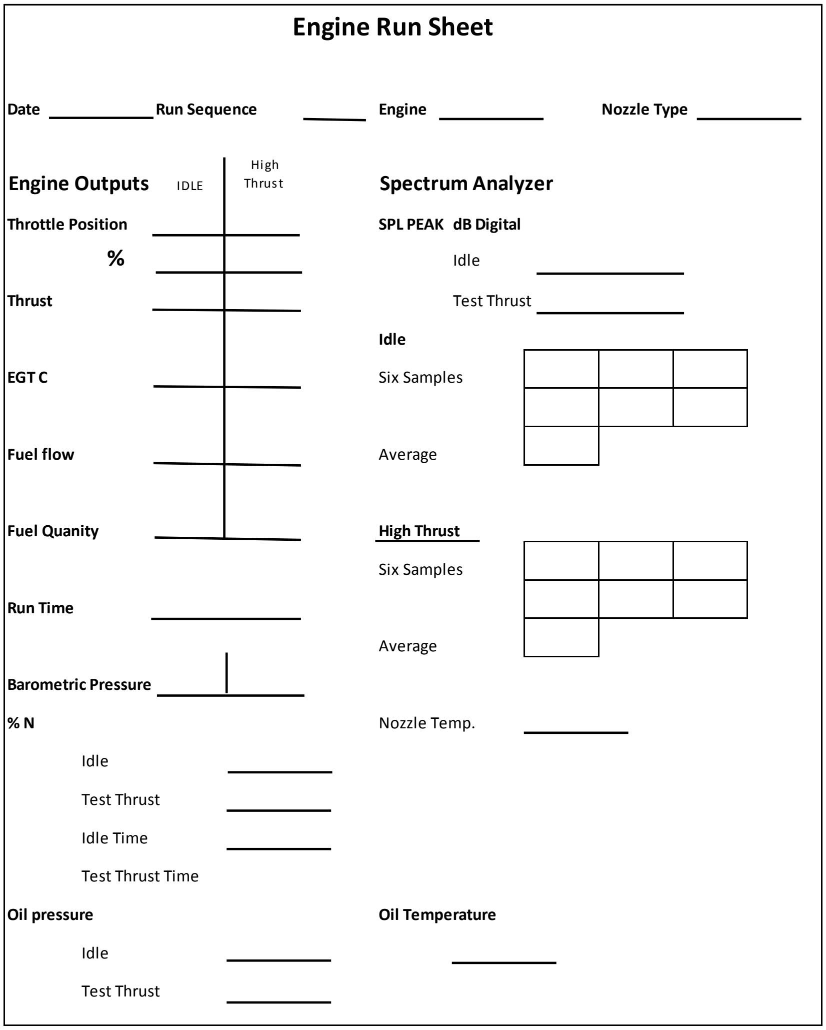
Figure 2: Thrust Test Cell

The testing was performed at an indoor turbine engine thrust test cell (see Figure 2). Sound was recorded by an Audio Control Industrial SA-3051 Spectrum Analyzer. This equipment is a measurement grade one third octave real-time analyzer. A CM-10 measurement microphone was mounted in a suspension holder on a stand sixty-eight inches high, placed twelve feet from the rear, and offset of the exhaust blast four feet. The analyzer recorded, stored, and averaged six samples of thirty different frequency dB levels at each test run of the three fabricated and the original nozzles. Each nozzle had samples taken at two different thrust amounts, idle thrust and one thousand lbs. thrust.

Data were manually recorded on a spreadsheet for comparison to the turbojet's original manufactured nozzle as shown in Table 1. Engine parameters, oil pressure, oil temperature, exhaust gas temperature (EGT), thrust lever position, fuel consumption, and engine run time were recorded. This information was collected during each test run on an Engine Run Sheet to determine any engine cycle changes (see Figure 3).

Frequency	1	2	3	4	5	6
25						
31.5						
40						
50				84		
63	84	84	88	84		84
80	92	96	92	92	92	96
100	96	96	96	96	96	96
125	96	96	96	96	96	100
160	96	100	100	100	100	100
200	104	104	100	100	100	104
250	100	96	100	100	96	100
315	104	100	100	100	100	100
400	100	100	100	100	104	100
500	104	104	104	104	104	104
630	100	104	104	100	104	100
800	100	100	100	100	100	100
1K	96	96	96	96	100	96
1.25K	100	100	96	100	100	100
1.6K	96	96	100	96	96	96
2K	96	96	96	96	96	96
2.5K	92	96	92	96	92	92
3.15K	96	100	100	100	96	96
4K	96	100	96	100	96	96
5K	100	100	100	100	100	100
6.3K	104	100	104	104	100	104
8K	108	108	108	104	108	108
10K	104	104	104	104	104	104
12.5K	104	100	100	100	100	100
16K	100	100	100	100	100	100
20K	96	96	96	96	92	92

Table 1: Data Recorded on a Spread Sheet for Comparison to the Turbojet's Original Manufactured Nozzle



Engine Run Sheet

Date ________ Run Sequence ______ Engine ________ Nozzle Type ________

Engine Outputs IDLE | High Thrust

Throttle Position

%

Thrust

EGT C

Fuel flow

Fuel Quanity

Run Time

Barometric Pressure

% N

Idle

Test Thrust

Idle Time

Test Thrust Time

Oil pressure

Idle

Test Thrust

Spectrum Analyzer

SPL PEAK dB Digital

Idle

Test Thrust

Idle

Six Samples

Average

High Thrust

Six Samples

Average

Nozzle Temp.

Oil Temperature

Figure 3: Engine Run Sheet

3: Results

Results were evaluated and compared to the original nozzle in three ways: (1) the effect of the nozzle designs in reducing noise by dB level, (2) frequency shift changes, and (3) change in the efficiency of the engine cycle parameters. Frequencies recorded were a function of the analyzer design. Results indicate that there were small differences between each of the test nozzles vs. the original nozzle. For clarity the thirty frequencies were divided into three groups for presentation of the results as shown in Table 2.

Low Group	Medium Group	High Group
25	250	2.5K
31.5	315	3.15K
40	400	4K
50	500	5K
63	630	6.3K
80	800	8K
100	1K	10K
125	1.25K	12.5K
160	1.6K	16K
200	2K	20K

Table 2: The Thirty Spectrum Analyzer Frequencies Separated into Three Groups

Figure 4 shows a table and graph of the average dB level at idle thrust for the four nozzles. The Chevron nozzle at idle had a 1.6 average increase in dB level over the original in all frequency groups. More of the frequencies in the first half of the frequency ranges had a higher dB level indicating a shift toward the low end of the range.

The Large Tab nozzle at idle had a 1.3 drop for the low group, a 1.20 increase for the medium group, and the same in the high group. In the low group the dB is initially lower, shifts toward the higher frequencies with an increased dB in the medium group, and decreases at the end of the high group.

The Small Tab nozzle at idle had a 1.3 dB drop in the low group, with a .40 and 1.20 increase in the medium and high groups.

Decibel Levels at Idle Thrust							
Frequency Group Averages	Original Nozzle	Chevron Nozzle	Change	Large Tab Nozzle	Change	Small Tab Nozzle	Change
Low Group	97.33	97.71	0.30	96.00	-1.33	96.00	-1.33
Medium Group	97.60	99.20	1.6	98.80	1.20	98.00	0.40
High Group	99.20	100.40	1.2	99.20		100.40	1.20
Change Average			1.60		-0.07		0.09

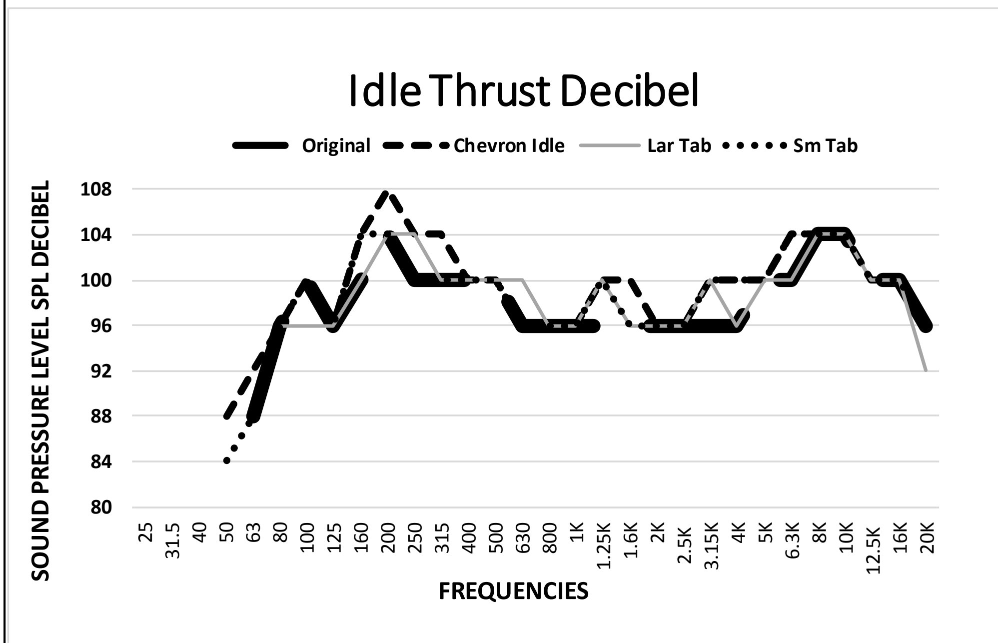


Figure 4: Decibel Levels at Idle Thrust for All Nozzle Designs

Figure 5 shows a table and graph of dB level for high thrust at 1000 lbs. for the four nozzles. The Chevron nozzle at 1000 lbs. thrust shows a .71 average increase in dB level over the original. It had a higher dB at the end of the low group without a shift. In the second half, it shows a shift at the end of the medium group and a reduction at the end of the high group.

The Large Tab nozzle at 1000 lbs. thrust had a .98 average increase in dB. The graph illustrates a shift to the higher frequencies at original nozzle dB level in the low group, a shift and dB increase in the medium, and a decrease at the end of the high group.

The Small Tab nozzle at 1000 lbs. thrust had a .36 average decrease in dB. The graph illustrates .94 average drop in dB in the low and medium group, and an .80 increase in the high group.

Decibel Levels at 1000 lbs. Thrust							
Frequency Group Averages	Original Nozzle	Chevron Nozzle	Change	Large Tab Nozzle	Change	Small Tab Nozzle	Change
Low Group	106.67	108.00	1.33	106.80	0.13	106.00	-0.67
Medium Group	108.80	109.20	0.4	110.00	1.20	107.60	-1.20
High Group	108.80	109.20	0.4	110.40	1.60	109.60	0.80
Change Average			0.71		0.98		-0.36

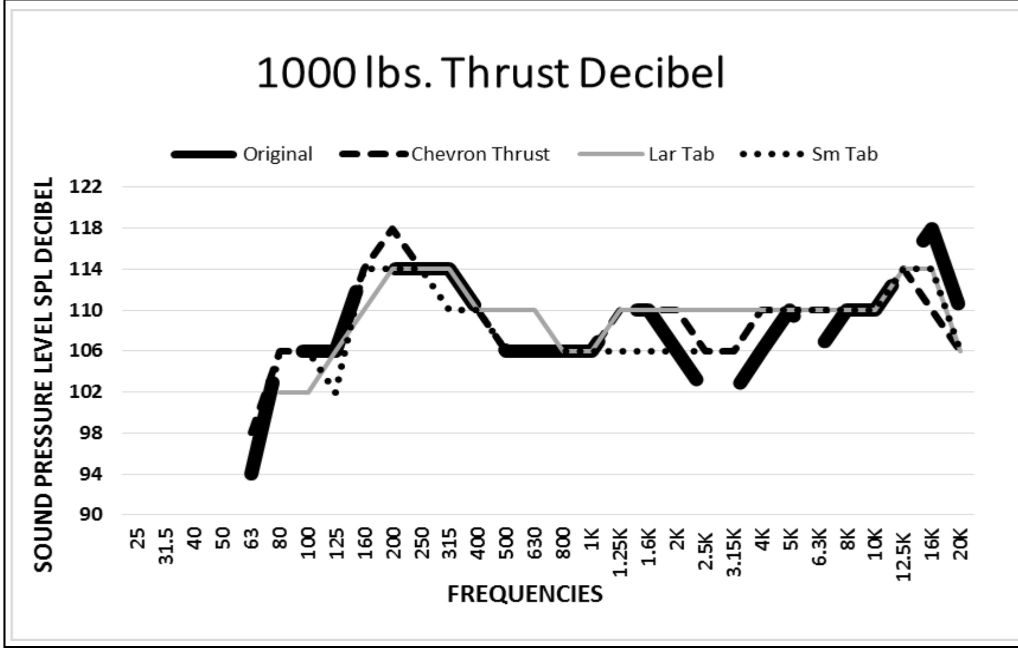


Figure 5: All Nozzle Designs at 1000 lbs. Thrust

Table 3 is a summary of engine output parameters. Throttle position, Exhaust gas temperature (EGT), Fuel flow, and % N (rpm) are the main engine outputs that indicate a change in cycle efficiency for the different nozzles.

Throttle position indicates the amount of scheduled fuel required for the target thrusts of Idle and 1000 lbs. EGT, the amount of heat at the discharge side of the turbine, will indicate if the turbine and exhaust components are exposed to critical temperatures. Fuel flow will determine the amount needed to maintain the target thrusts and %N will indicate the amount of rpm required for the target thrusts.

Throttle position varied very little with the original nozzle having the largest amount of travel for an increased amount of scheduled fuel.

EGT for the original nozzle was the lowest, while all three of the turbofan nozzle designs showed an increase. The smallest amount of increase for idle was 9.5% and 13% for the higher thrust target. These increases were close the critical EGT for this engine at 525 degrees centigrade. This indicates that these nozzle designs were restricting the gas flow.

Fuel flow shows the Large Tab being the lowest for idle, and the original nozzle being the lowest for the higher thrust target. This indicates the exhaust paths for these two nozzles were more efficient at those thrusts levels.

Reviewing just the three turbofan nozzles for comparison, the Large Tab at the idle thrust had the smallest throttle position, the lowest EGT, lowest fuel flow, and required the least amount of %N rpm.

Type of Nozzle	Original		Chevron		Large Tab		Small Tab	
	Idle	1000lbs	Idle	1000lbs	Idle	1000lbs	Idle	1000lbs
Throttle position in %	10.21	33.3	8	31.1	9.1	32.2	10.2	31.9
Thrust	340	1000	340	1000	340	1000	340	1000
Exhuast Gas Temp. (EGT)	459	453	536	533	502	517	515.3	511.4
Fuel Flow	609	987	663	1050	607	1095	640	1045
Oil pressure	44.3	44.6	41.5	43.7	44.5	44.7	42.3	43.5
Run Time	220sec	141sec	482sec	157sec	319sec	175sec	392sec	125sec
Barometric Pressure30.03	29.51	29.48	29.38	29.37	29.42	29.39	29.4	29.42
% N (rpm)	42.8	69.2	43.87	56.55	42	65.2	42.7	65.3
Sound Press. Level (SPL)	112.8	123.1	113.6	123.1	113	123.4	112.8	122.8
Fuel Quant. Gal Per min.		0.751		0.554		0.657		0.623
Nozzle Temp. Inside		439		389		390		413
Nozzle Temp. outside		198		365		250		226
Tab temp.				389		285		281
Oil temp.		67.6		67.7		68.4		64.7

Table 3: Engine Outputs Parameters

4: Discussion and Conclusions

One of the objectives for this project was to find an alternative to older retrofit designs to reduce noise in turbojet engines. Research on noise reduction has increased in the last ten years mainly due to the world regulatory agency noise standards. New designs and methods of research created a number of nozzle reconfigurations that are part of the turbofan engine design and not a retrofit. After reviewing available materials related to these recent reconfigurations of nozzle, it was found that the majority was performed on turbofan engines. The idea that since the increase in the amount of research and methods on alternative noise reduction systems for turbofan engines with less negative effects on aerodynamic characteristics and cycle efficiencies, could also be a cost effective system for other types of turbine engines.

The overall results indicate that the turbofan nozzle designs used in this research project did not make any major improvements in reducing the overall noise. There were reductions of dB levels for some specific frequencies. Frequency shifts were apparent in all nozzle designs and most shifts were toward the higher frequencies that may have reduced some noise. The equipment used was limited, being able to record only thirty frequencies. Further research could benefit by using equipment that could separation a greater number and range of frequencies.

The engine cycle efficiencies were degraded by these nozzles as compared to the original. Alternate designs that do not penetrate the gas path could reduce the negative effects on engine parameters.

Historical engine noise policy implies that world regulatory agencies will most likely move to reducing the amount of noise permitted for turbine powered aircraft in the future. Turboprop and turboshaft engines used on smaller transport aircraft and helicopters that are not all currently regulated may be in the future. The designs used in this research or similar designs should be considered for these types of engines.

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